White Paper for the AAAC ExoPlanet Taskforce

Finding Exoplanets around Old and Young Low-Mass Stars

Steven Pravdo, Stuart Shaklan, David Redding, Gene Serabyn, & Bertrand Mennesson
Jet Propulsion Laboratory, California Institute of Technology
April 2, 2007

ABSTRACT

A cost-effective, high-precision astrometry program will discover a thousand exoplanets around low-mass stars, the 70% of all stars that are now under-represented in planet searches, and measure their dynamical masses. A ground-based precursor of the comprehensive ground- and space-based program proposed herein has proven the concept. The state-of-the-science now has a sensitivity of 1 milliarcseconds in long-term observations, able to detect Jupiter-mass planets around M-dwarfs. An advanced coronagraph also being proven on the ground can achieve high contrast ratios at close separations and complement the astrometric results. We describe the existing programs, the path to ground-based improvements, and the extension of this path into a space-based program that fits with margin in the medium-cost class of space missions.

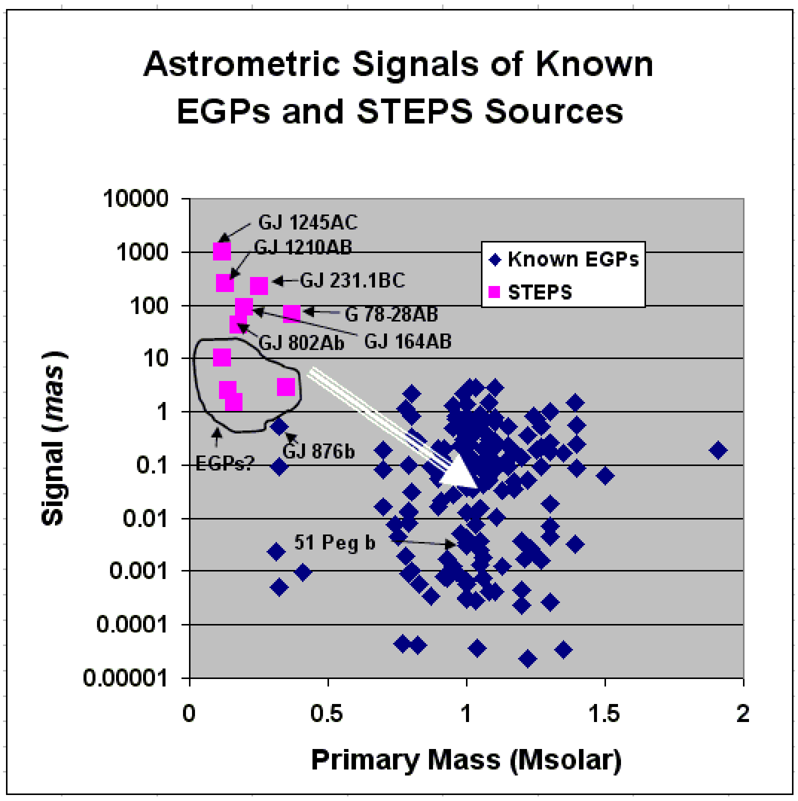

Figure 1. Current STEPS astrometric results and radial velocity (RV) planets in the parameter space of astrometric signal vs. primary mass. The white arrow illustrates where higher precision and dynamic range lead to in planet discoveries and in the first unambiguous mass measurements of many RV planets.

1. SCIENCE: We describe a program of astrometry and coronagraphy that can make significant progress in an area that is now largely unexplored; *viz.* the properties of exoplanets around low-mass stars, both old and young. With a ground-based astrometric program we can find exoplanets and measure their dynamical masses unambiguously down to 1 Jupiter-mass (M_J) around hundreds of stars, thereby significantly increasing their inventory. A space-based evolution of that system lowers the mass limit to 0.2 M_J and raises the number of targets and discoveries by another factor of ten, enough to perform class studies.

Astrometry is an exoplanet-discovery technique with historical promise that can now complement radial-velocity[1] (RV) and other searches because its precision has reached that of the known astrometric signals of planets. Measuring the dynamical masses of companions without the inclination angle ambiguity of RV detections is important because all physical models are driven by the masses. The frequency of EGPs around low-mass stars is poorly known leaving unanswered a fundamental theoretical question about whether such planets form inefficiently via core accretion[2] or efficiently via disk instability.[3]

A *raison d'etre* of exoplanet research is the discovery of Earth-like planets. Our program is most sensitive to extrasolar giant planets (EGPs) that lie farther from their stars than any terrestrial planets' habitable zone, as in the solar system. In addition, we are sensitive to planets around young stars, thereby allowing direct testing of planet formation and migration theories over a wide range of planet masses, orbits, and ages.

Coronagraphy complements the astrometry both by measuring the same companions, and thus solving all the system parameters, and by discovering companions in outer stellar regions where the astrometric time-baseline is insufficient. For older stars with ages ≥ 200 Myr, coronagraphy can detect brown dwarf (BD) companions down to 12 $\boldsymbol{M_J}$ from the ground and planets to 4 $\boldsymbol{M_J}$ from space. For star ages 1-200 Myr coronagraphy extends the mass ranges down to 2 $\boldsymbol{M_J}$ from the ground and 0.5 $\boldsymbol{M_J}$ from space.

The IR flux from an EGP or BD is self-generated and thus independent of the distance to its star, allowing favorable contrast ratios far from the star, especially in younger stellar systems (≤ 200 Myr). A recent review[4] states, "In the late 1990s the TW Hydrae Association, the Tucana/Horologium Association, the β Pictoris Moving Group and the AB Doradus Moving Group were identified within ~60pc of Earth, and the η Chamaeleontis cluster was found at 97 pc. These young groups (ages 8-50 Myr), along with other nearby, young stars, will enable imaging and spectroscopic studies of the origin and early evolution of planetary systems." There are about 50 additional nearby stars (<30pc) observable from the northern hemisphere that show Li excitation lines at the Pleiades level or higher[5], indicating a maximum age of 100 Myr. The bulk of these young nearby stars have near-IR (NIR) magnitudes of 4-7, making them prime candidates for a coronagraph. So far no program has reported any direct detection of young planets around these stars, with the possible exception of a ~5 $\boldsymbol{M_J}$ companion orbiting 55 AU from a BD (age ~8 Myr)[6]. Such direct detection programs use adaptive-optics-assisted coronagraphy, and are thus more sensitive at relatively large separations.

In what follows we describe a ground and space program to search for EGPs around low-mass stars, ~70% of all stars. Our program is designed to overcome the observational selection effects (dim primaries, complex spectra, variability, etc.) that now limit the known planets around low-mass stars to only ~3% of the ~215 known planets.

2. STATE OF THE TECHNOLOGY:

2.1 Astrometry. The Stellar Planet Survey (STEPS) instrument is a 4K x 4K CCD camera located at the Cassegrain focus of the Palomar 200" (P200) telescope. STEPS performs the world's best long-term (10 years) relative astrometry of low-mass stars and has demonstrated its precision by finding low-mass binary companions and BDs around M-stars[7]. Only the Hubble Space Telescope Fine-Guidance Sensor shows a comparable long term precision of ≤1 milliarcsecond (*mas*). STEPS can find the first astrometrically discovered EGP by continuing its observations to achieve the required temporal baselines and orbital phase coverages. Fig. 1 shows the astrometric signals of many of the known EGPs. GJ 876b, one of the ~7 planets around M dwarfs[8] is labeled. The location of the STEPS detections of M-dwarf companions and possible EGPs (enclosed region) is illustrated. The next generation ground and space astrometric instruments extend the STEPS-sensitive region downward in the plot because of higher precision and to the right because of higher dynamic range (white arrow). This allows both thousands of new discoveries and unambiguous mass determinations of ~100 RV planets. The performances of the ground- “P200 astrometry” and the “Space astrometry” systems are illustrated in Fig. 2 where the region explored is above the marked diagonal lines. At the shortest periods (to the left) the minimum masses are 1 $\boldsymbol{M_J}$ for young stars at 60 pc and 0.2 $\boldsymbol{M_J}$ for old stars at 10 pc.

***Signals and Targets*:** The astrometric signal, **Θ,** of a planet ($\boldsymbol{M_J}$ units) around a star $\boldsymbol{M_{.2\odot}}$ (0.2 Solar-mass) units, is:

$$\boldsymbol{\Theta = 0.96\,(a/d_{10})\,(M_J/M_{.2\odot})} \qquad \textit{mas} \qquad \textbf{(1)}$$

where $\boldsymbol{a}$ is the semi-major axis (AU) and $\boldsymbol{d_{10}}$ is the distance (units of 10 pc). There are ~1000 known M-dwarfs <20 pc in the northern sky[9] alone and nearly 600 L and T dwarfs[10], another target class.

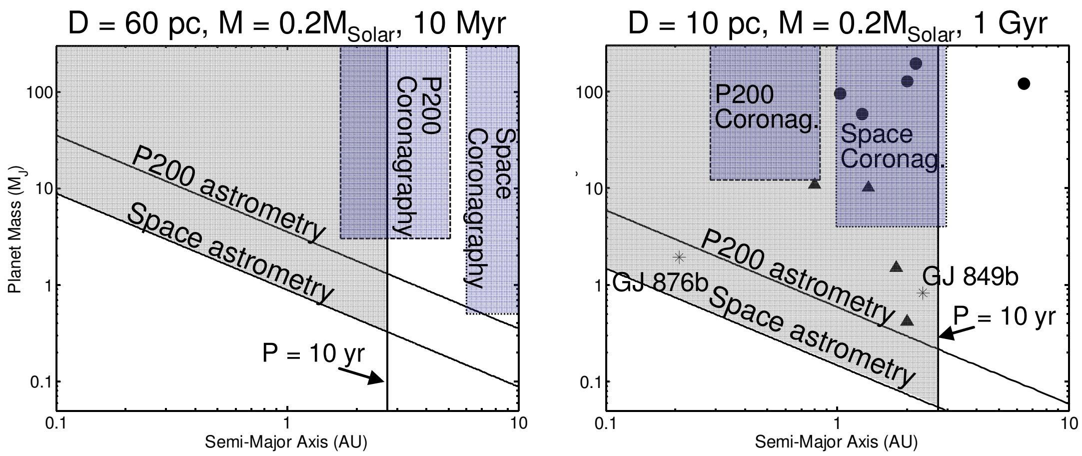

Figure 2. Planet mass ($\boldsymbol{M_J}$) vs. semi-major axis (AU) parameter spaces available to astrometry and coronagraphic imaging for exoplanets around low-mass stars: left is young stars (10 Myr) and right is old stars (1 Gyr). Two RV planets around M stars, GJ 876b and GJ 849b (asterisks), STEPS discoveries (dots), and STEPS searches (triangles) are shown in the right panel.

Sources of Noise: With the STEPS program we have become experts in the identification and mitigations of the sources of noise is ground-based astrometry. Note however that all of the effects except the refractive dynamic atmospheric effects also occur in space. Systematic effects limit STEPS’ performance to 0.5–1 *mas* rms, compared to the nightly shot- and atmospheric-noise limit of 0.25-0.4 *mas*. STEPS sees evidence of refractive, spatial, electronic, and other instrument-related effects, and these have both static and time-varying components (Table 1). Effective color is a dominant

Table 1. Astrometric Noise

Type	**Static**	**Dynamic**
Refractive	DCR, stellar color errors	atmosphere, stellar color variations
Spatial	step & repeat errors	telescope PSF
Window	scratch dust	variable contaminants
Flat field	QE	scattered light
Electronic	linearity	amplifier drift

systematic error in past work[11] and it is likely dominant in STEPS as well. The amplitude of the RA and Decl. differential chromatic refraction (DCR) correction is tens of *mas* relative to the reference frame. There is some evidence in STEPS data of significant nightly variations (1 *mas* at 45^o zenith angle) in the refraction of the atmosphere. CCD step-and-repeat errors are common and can cause significant astrometric errors. Several years ago we invented and applied a technique to globally characterize the astrometric uniformity of WF/PC II CCDs and found that they have 0.5 μm errors (1 *mas* in the Wide Field Camera) every 34 rows.[12] Variability in the telescope point-spread function (PSF) with changing conditions (e.g. temperature) leads to measurement noise.

Window imperfections (dust, scratches, and pits) are also potentially significant sources of error that we mitigate by dithering the telescope frame-by-frame in a 1" square pattern. Calibration at the telescope shows this effect is ~0.2 *mas*.

Asymmetric telescope aberrations and variable seeing conditions cause wavelength-dependent centroid shifts. The amplitude of the shift depends on the aberration and the centroiding algorithm. The centroider errors are ≤1 *mas* if the combined seeing and aberrations are <2".

Solid state detectors typically have pixels with static quantum efficiency (QE) differences of several percent, and a small fraction of dead or "hot" pixels. These are dealt with by calibration and median filtering, and by dithering. On a larger spatial scale, scattered moonlight and starlight leaves a distinctive pattern on the detector caused by multiple reflections in the telescope baffling. This adds noise to moonlit observations.

Finally, CCD electronic effects, potentially time variable, are another important source of systematic error. The STEPS CCD is a single piece of silicon but is read out via 4 amplifiers. There is evidence in the data of timing drift between amplifiers that leads to apparent quadrant shifts of a significant fraction of a pixel. These are largely correctable,

2.2 Coronagraphy. We are developing a conceptually simple "fiber nuller" coronagraph[13] in which a relative phase flip of π radians is introduced between the two halves of the focusing telescope aperture, and then a single-mode fiber is placed at the location of the center of the focal plane PSF. In this approach[14], the central PSF lobe is bisected by a central linear dark fringe, so that the on-axis starlight is nulled, while light from off-axis planetary companions within the fiber's single mode field of view is transmitted by the adjacent pair of off-axis bright fringes. Because the single mode fiber acts in essence as a power transmitter, the location and flux of the stellar companion is determined by rotating the fringes, via a pupil rotation, such as a telescope rotation in space. The resultant optical scheme is then very simple: leaving aside the wavefront controller and deformable mirror (DM) which are present anyway, one simply puts a π phase shift onto the DM or a fixed phase plate, and then situates a single-mode fiber in the normal focal plane. This approach is now being implemented on the P200 telescope, and because of its simplicity can quickly be adapted to other telescopes.

The fiber nuller enables observations at unprecedented levels of angular resolution, reaching inner working angles, IWA ~ $\lambda/2.5\boldsymbol{D}$, where $\boldsymbol{D}$ is the telescope aperture. This is ~30 *mas* at the P200, or 0.6 AU at 20 pc! The expected contrast achievable on the ground[15] is 10^{-4}. To date the best ground-based result is 4 x 10^{-3} at 200 *mas* using the VLT[16]. In space, HST/NICMOS has the smallest IWA at 300 *mas*. The JWST coronagraph will not achieve high contrast within 0.5" of the optical axis.[17] Thus, the expected IWA of the fiber nuller coronagraph is smaller than these by roughly an order of magnitude. Such an angular resolution gain is already evident in the case of non-redundant aperture masking[18], but the contrast is limited to 10^{-2}.

3. GROUND-BASED PROGRAM & UPGRADES

3.1 Astrometry: We have identified two steps to upgrade the ground-based search effort. The first is to improve the visible-band instrument. We would increase the signal by a factor of 2 with a commercial-off-the-shelf (COTS) backside-illuminated large-format CCD and decrease the noise by upgrading the electronics. This would result in a factor >2 higher signal-to-noise for a small hardware cost.

The second step is to move the observing regime into the NIR, either at 1.25 μm (***J***-band) or 1.65 μm (***H***-band). Again this would increase signal because the bulk of the luminosity from the low-mass stars comes in this spectral region, and decrease noise because differential color terms are lessened in the NIR, while other NIR-related sources of noise can be effectively mitigated. A prototype of this instrument is proposed to the 2007 NASA/APRA2 program to demonstrate in the laboratory and at a ground-based observatory that the projected improvements are real: *viz*., high-precision astrometry with a HgCdTe array and Hawaii-2RG (H2RG) readout, and a 10^4 increase in dynamic range via electronic windowing. The latter allows much brighter targets to be observed simultaneously with dimmer reference stars, without a loss of astrometric precision.

Atmospheric dispersion in the NIR is 40% of that in the STEPS band at 0.65 μm. By choosing a filter that is 0.1 μm wide (compared to the STEPS bandpass of 0.55-0.75 μm), the systematic effects are reduced by another factor of two. The electronics-related systematics (e.g. readout latency) are uncertain but the H2RG device affords greater control over the readout patterns and more freedom to adjust the device operation than with the CCD. The optics issues including window quality, coating pinholes, and dust will be roughly the same in the NIR as for STEPS. Our modeling shows that the 1/30 wave window contributes <0.1 *mas* errors, while our tests of the influence of pinholes and dust using real stellar images show worst-case effects of similar magnitude. Other effects such as image latency and OH airglow have yet to be characterized for this application. Still, the upgraded system is predicted to achieve 0.2-*mas* rms noise, a significant improvement. Most of the cost associated with this new instrument is for the COTS sensors.

3.2 Coronagraphy: The distribution of known exoplanet separations peaks within one AU. This result is biased by the RV detection method, which is more sensitive to closer separations, yet it is an existence proof of massive planets in this inner region of the stellar environment. The fiber nuller would examine the validity of this result in the case of young stars, which are too active for RV searches, constitute too small a sample for transit searches (plus the variability issue), and which can not be observed at the same resolution by other direct imaging techniques. Cool, low-mass stars also provide the advantage of deeper diameter-limited null depths, because of their smaller sizes. Models of stars in this age regime[19] predict, e.g., that a 2 M_J companion can be imaged around a $M_{.2\odot}$ star with the 10^{-4} dynamic range. The sensitive region of parameter space for the ground instrument is labeled "P200 Coronagraphy" in Fig 2. There is significant overlap with the astrometry for both populations of stars.

4. SPACE-BASED PROGRAM: Astrometry as described above, combined with coronagraphy on a space-based mission, offers a path that ends with a thousand planet discoveries and characterizations for a cost and in a schedule that is modest in comparison with the missions that require substantial technological research and development. A key element of this science- and cost-driven effort is the use of an available, light-weighted 1-m class aperture. The aperture can supply light to both instruments, directly for the astrometry and via a mask assembly for the coronagraphy.

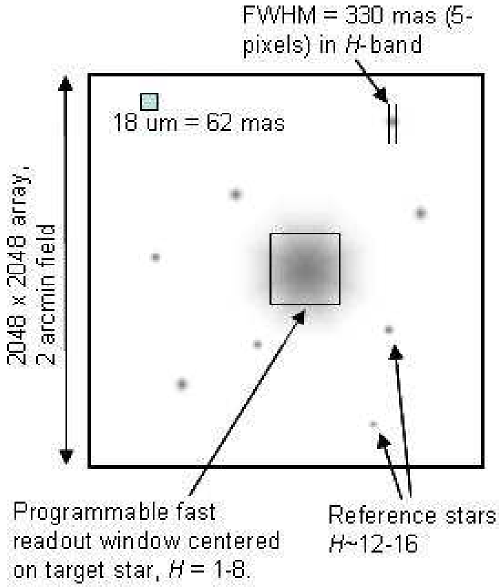

Figure 3. Windowed operation of the astrometric focal plane.

4.1 Astrometry in space would benefit from the lessons learned in the upgraded ground program and the absence of atmospheric noise sources. Without atmospheric seeing the diffraction limited image in the NIR for a 1-m aperture is λ/D ~ 0.3." This is a factor of three improvement from the typical seeing disk from the ground. We estimate achieving an rms error of 0.05 mas (50 μas) in space, or a factor of 4 better than the ground estimate. Figure 3 illustrates the operation of the astrometric focal plane that uses windowing to achieve high dynamic range.

The number of targets from space increases by the distance cubed while the astrometric precision decreases by the distance allowing the same precision from the ground for 64 times more targets. Tens of thousands of targets are thus accessible for the planet searches.

4.2 Coronagraphy: A space-based telescope brings several advantages, including pathlength stability and thus the ability to observe fainter targets (too faint for very rapid ground-based adaptive optics systems). With aperture D = 1 m and wavelength λ = 1-2 μm, the theoretical null depths for M stars are in the 10^{-6} to 10^{-7} range. At the same time, the IWA is 130 mas. The space-equivalent to the ground DM is an available, light-weighted primary.

Signal and separation: The increase in the achievable contrast ratio in space from ~10^{-4} to at least 10^{-6} allows the space coronagraph to detect smaller companions, albeit at larger separations because of the smaller $\boldsymbol{D}$. The minimal observable separation, $\boldsymbol{a_{min}}$ is

$$a_{min} = 0.86\ (\lambda\, d_{10} / D)\ \ \mathrm{AU} \qquad (2)$$

where λ is the observing wavelength (µm), $\boldsymbol{D}$ is the aperture size (m). Fig. 2 shows that "Space coronagraphy" explores a search space region complementary to astrometry for the young stars and overlaps the astrometric search space for old stars.

***4.3 Mission Cost*:** Preliminary cost models show that a concept combining an available, light-weighted meter-class mirror and astrometric and coronagraphic instruments can comfortably fit within the medium-class mission cost cap.

5. CONCLUSION: We seek concurrence from the ExoPlanet Task Force, and the broader scientific community, for our program of simple, straightforward technologies that enable cost-effective space missions with small apertures and can first be demonstrated cheaply on ground based-telescopes. With astrometry and coronagraphy we will find and characterize planets around a significant sample of the 70% of stars that are not well-sampled at present or targeted by other future missions. The stars are the thousands of nearby low-mass stars, most of which are contemporaries of the Sun, and others in the closest younger stellar systems.

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